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BIMODAL ABUNDANCES IN THE ENERGETIC PARTICLES OF SOLAR AND INTERPLANETARY ORIGIN

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ABSTRACT

This *Letter* reports the first results from an examination of the daily-averaged abundances of the elements from H through Fe as well as electrons and isotopes of He in energetic particles observed in interplanetary space by the *ISEE 3* spacecraft over an 8.5 yr period. The abundances of heavy elements such as Fe/O show, for the first time, clear evidence of the presence of two distinct populations of particles. Earlier observations could be interpreted as extreme variations within a single population. The population with enhanced Fe/O shows correlated enhancements in ^{3}He/^{4}He, *p*/*e*, and He/H. This population is consistent with material that has been processed to high temperatures in the impulsively heated regions of solar flares. The second population, with more normal abundances, is probably accelerated from ambient material by coronal and interplanetary shocks.

Subject headings: interplanetary medium — Sun: flares — Sun: solar wind

I. INTRODUCTION

Several years ago Mason *et al.* (1980) surveyed the energetic particle abundances observed in interplanetary space during the 1973–1977 solar-minimum period. This survey was based upon daily-averaged intensities of the dominant elements from H through Fe, and, since all types of particle increases were included, it provided an unbiased context in which to investigate element enhancements such as those accompanying ^{3}He-rich solar flares, for example. The advantage of the technique used by Mason *et al.* (1980) is that it does not reject events as being too small, too complex, or too difficult to identify, and it makes no assumption about the constancy of abundances during all phases of an event.

Recent studies of flare-associated particles have shown that variations in particle composition are associated with different acceleration mechanisms that can be distinguished by differences in the X-ray and radio properties of the parent flare. Two classes of flare events are observed (Cane, McGuire, and von Rosenvinge 1986; Reames and Stone 1986; Cane and Reames 1988; Reames *et al.* 1988) to produce differing electron/proton and ^{3}He/^{4}He ratios. Class I (first-phase) events have impulsive soft X-ray profiles and are accompanied by type III and V radio bursts. Particles from these events have greatly enriched abundances of electrons and ^{3}He. Class II (second-phase) events have gradual soft X-ray profiles, and they are accompanied by coronal mass ejections and by type II and type IV radio emission. These flares are responsible for most of the large proton events seen at Earth (see also Kahler *et al.* 1984). At times, both mechanisms occur in a single large event that exhibits all four types of radio emission and, presumably, accelerates both populations of particles.

Enhanced abundances of heavy elements up to Fe have been known for some time to accompany ^{3}He-rich events (see, for example, Hurford *et al.* 1975; Anglin, Dietrich, and Simpson 1977; Mason *et al.* 1986; Mason 1987). These heavy elements are observed to have a higher charge state than those from large proton events (Klecker *et al.* 1984; Luhn *et al.* 1985) suggesting that they come from a higher-temperature environment. Recently, the abundances of heavy elements have been directly observed to increase with the soft X-ray temperature in the flare that produced the ^{3}He-rich event (Reames 1988).

The foregoing observations have led to the suggestion (Lin 1987; Reames 1988) that the enhanced abundances might occur in the material that is heated impulsively in the flaring region itself, while the abundances observed in large proton events represent the more normal ambient coronal abundances that are accelerated by shock waves propagating outward through the corona. If this suggestion is correct, the two classes of solar event might produce two particle populations with very distinct heavy-element abundances arising from two different acceleration mechanisms. All previous observations of particle abundances, however, could be interpreted as variations within a single distribution; only indirect evidence suggested a bimodal distribution.

In order to investigate this question, we have studied the daily-averaged particle abundances observed on *ISEE 3* during an 8.5 yr period from 1978 to 1987. Since this period included solar maximum, we were able to obtain significant abundance measurements on nearly 600 days, a sample that is almost 4 times larger than that of Mason *et al.* (1980).

II. OBSERVATIONS

All of the observations reported here were obtained with the Medium-Energy Cosmic-Ray Experiment (von Rosenvinge *et al.* 1978) aboard the *ISEE 3* spacecraft. For most of the observation period, the spacecraft was in orbit about the Sunward libration point; during 1983 December, however, the spacecraft undertook a cometary mission and began moving ahead of Earth in solar orbit. The study period began 1978 August 15 and ended 1987 February 7. It included 2896 days during which measurements were obtained. Coverage of the spacecraft fell precipitously to a few hours a day during the latter phase of the mission, however, so that the latter time period is statistically underrepresented.

The primary study included the elements C, N, O, Ne, Mg, Si, S, Ca, and Fe measured in the Very Low Energy Telescopes (VLETs) and accumulated in the intervals 1.9–2.8 MeV per

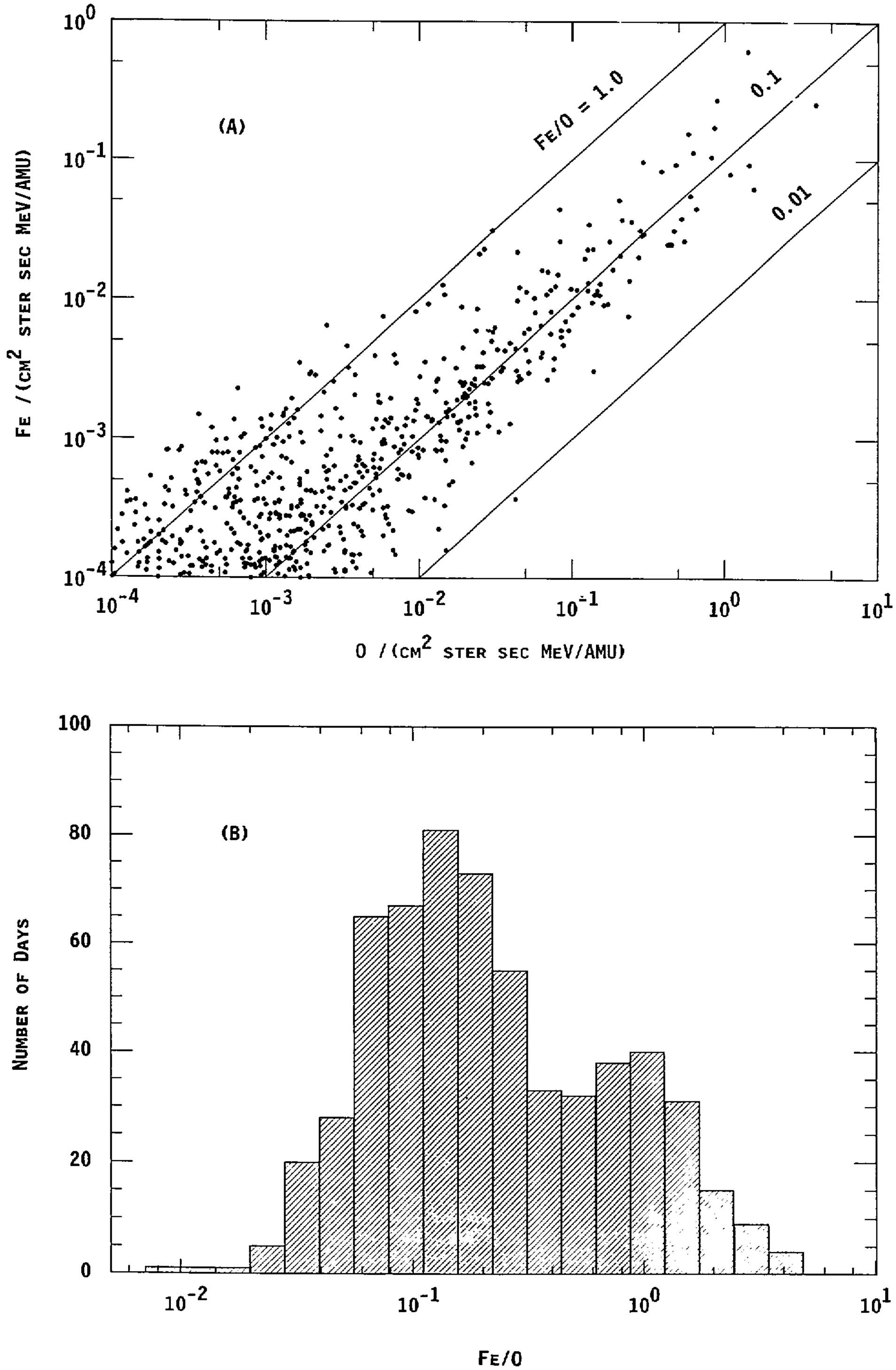

FIG. 1.—Daily averaged intensity of oxygen vs. that of iron in the 1.9–2.8 MeV per amu interval is shown in (*a*) for the 598 days that exceed the lower bounds of the plot. The histogram in (*b*) shows the corresponding distribution in the Fe/O ratio for the same days. The plots show evidence of two separate particle populations with Fe/O ratios that differ by an order of magnitude.

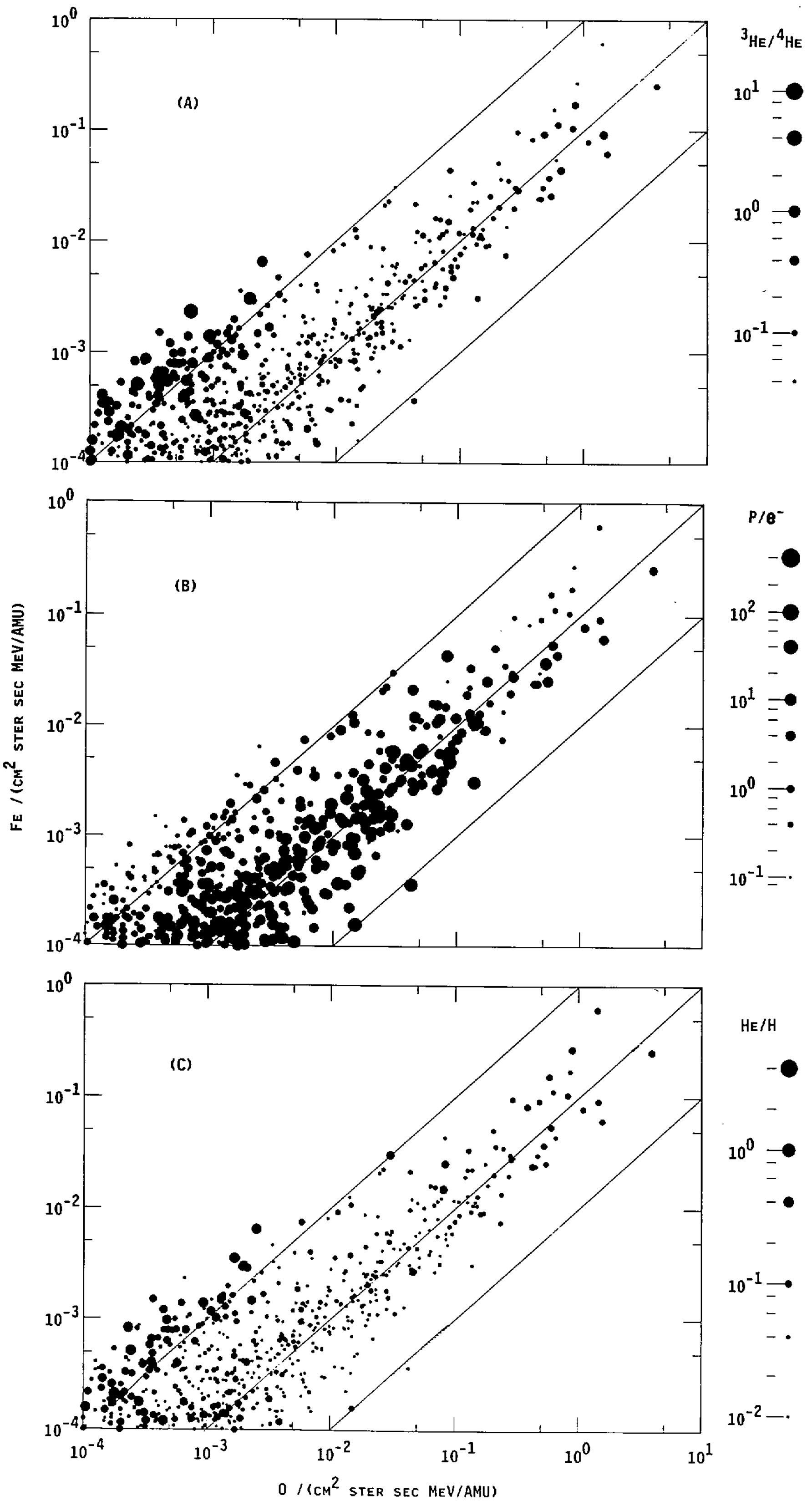

FIG. 2.—Each panel shows the same points plotted in Fig. 1*a*; however, the symbol size at each point varies with a parameter as shown to the right of the panel. The parameters are the ^{3}He/^{4}He ratio in (*a*), the proton/electron ratio in (*b*), and the He/H ratio in (*c*) (see text). These associated parameters highlight the difference in the two Fe/O populations.

amu, 4.0–7.0 MeV per amu, and 7–12 MeV per amu. He isotopes in several energy intervals and H at 1–4 MeV were also measured in the VLET, while electrons above about 0.22 MeV and protons above 4.4 MeV were measured in the High Energy Telescopes (HETs). Examples of the element and isotope resolution on which these measurements are based are shown in von Rosenvinge and Reames (1979) and Reames, von Rosenvinge, and Lin (1985).

Figure 1 shows the Fe and O observations in this study. Figure 1*a* shows a plot of the Fe intensity versus the O intensity on all days when the intensity of both species exceeded 10^{-4} particles/(cm^2 sr s MeV per amu) or about 4 particles per day. A total of 598 points appear on the plot. Figure 1*b* shows the distribution of the same events in the Fe/O ratio. Both the intensity plot and the histogram show evidence for two populations of particles, separated by about an order of magnitude in their value of Fe/O.

In order to demonstrate the correlations and help us to identify the origin of the particles, the data from Figure 1*a* have been replotted in each panel of Figure 2, with the symbol size for each data point allowed to vary with the value of a third parameter as shown to the right of the panel. In Figure 2*a*, the symbol size varies with the ^{3}He/^{4}He ratio (at 1.3–1.6 MeV per amu), in Figure 2*b*, with the proton/electron ratio (4.4–6.4 MeV protons and 0.22–2.0 MeV electrons), and in Figure 2*c*, with the He/H ratio (1.1–4.0 MeV per amu).

Referring to Figure 2, days that would be described as Fe-enhanced would also be described as ^{3}He-rich, electron-rich, and proton-poor. These properties have been previously associated with particles from impulsive solar flares and many of those flares have already been identified (Cane, McGuire, and von Rosenvinge 1986; Reames and Stone 1986; Reames *et al.* 1988). This knowledge of the properties of the parent flares was not available during earlier work on heavy-element enhancements.

Care should be exercised that the individual numerical values in the figures are not interpreted too literally. Individual days can include multiple solar events or parts of events that give improper averages. The electron measurements, in particular, can be affected by background or by saturation effects in large events. We believe that the ensemble of measurements provides the correct understanding of the associations even though individual averages are flawed.

III. DISCUSSION

Over 27% (163 of 598) of the days studied in Figure 1 showed an average Fe/O ratio of 50% or larger. This rate of occurrence is surprisingly large considering that impulsive particle events have short durations while large proton events and interplanetary shock events often last several days. Because of their somewhat lower intensities, the Fe-rich and ^{3}He-rich events were once considered to be rare.

Each of the 163 Fe-rich days has been examined using high time resolution data. Often, periods of several days are found that contain multiple impulsive events from a single active region. These events are easily identified by associated electron increases occurring within minutes of the flares. Similar behavior was reported for ^{3}He-rich events (Reames, von Rosenvinge, and Lin 1985; Reames and Stone 1986). Only about half of the time periods with Fe/O > 0.5 are identified as ^{3}He-rich, and conversely, not all of the ^{3}He-rich events have enhanced abundances of Fe, presumably because of insufficient heating (Reames 1988).

Evidence for a bimodal distribution can also be seen in elements other than O and Fe, but it is seen most clearly in these two species since they are widely separated in charge. Furthermore, Fe alone (among measurable species) retains orbital electrons at the high temperatures of impulsive flares (Reames 1988) and is susceptible to enhancement by the Fisk (1978) mechanism (see also Varvoglis and Papadopoulos 1983).

At higher energies the Fe/O ratio shows comparable separation of the two populations, but unfortunately, with much poorer statistics since there are fewer days of observation. It should be noted, however, that correlations between the composition and the energy spectral index have been seen in a wide variety of observations. Such correlations of abundance ratios with spectral index have been seen in electron measurements (Guzik 1988; Evenson *et al.* 1984), in Fe and O measurements (McGuire, von Rosenvinge, and McDonald 1986), in ^{3}He measurements (Reames and von Rosenvinge 1983) and in the less abundant ions (Breneman and Stone 1985). We are not aware of any suitable explanation for this widespread correlation between composition and spectra.

The events with low values of Fe/O include the unresolved contributions of large proton events (the long-duration events of Cane, McGuire and von Rosenvinge 1986) and of interplanetary shock events. Recent studies (Cane, Reames, and von Rosenvinge 1987, 1988) point out that interplanetary shocks make a much larger contribution to the observed interplanetary particles from solar events than previously believed. A preliminary study shows that many of the days with the lowest Fe/O in Figure 1 are days of passage of interplanetary shocks. It also seems possible that several large events in which the Fe/O ratio decreases with time (such as the 1978 September 23 event studied by von Rosenvinge and Reames 1979) could consist of an impulsive flare component with high Fe/O followed by a gradually increasing shock component with a low value of Fe/O that is in agreement with abundances in the corona and solar wind. These observations suggest that particles from the flare do not serve as a seed population for further acceleration by the interplanetary shock.

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